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THE NASA COSMIC RAY PROGRAM FOR THE 1990'S AND BEYOND

Interim Report of the NASA Cosmic Ray Program Working Group

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ABSTRACT

The interim report of the 1989 NASA Cosmic Ray Program Working Group is presented. The report summarizes the cosmic ray program for the 1990's, including the recently approved ACE, Astromag, HNC, POEMS, and SAMPEX missions, as well as other key elements of the program. New science themes and candidate missions are identified for the first part of the 21st Century, including objectives that might be addressed as part of the Human Exploration Initiative. Among the suggested new thrusts for the 21st century are: an Interstellar Probe into the nearby interstellar medium; a Lunar-Based Calorimeter to measure the cosmic ray composition near $\sim 10^{16}$ eV; high precision element and isotope spectroscopy of ultraheavy ($Z \geq 30$) elements; and new, more sensitive, studies of impulsive solar flare events.

1. INTRODUCTION

This interim report of the 1989 NASA Cosmic Ray Program Working Group is based on the results of a workshop on the NASA Cosmic Ray Program for the 1990's and Beyond which was held at the Goddard Space Flight Center on November 6-8, 1989. The workshop involved more than 50 members of the cosmic ray research community who contributed to the discussion and identification of future objectives and missions. The Cosmic Ray Program Working Group met immediately after the workshop in order to formulate the program presented in this interim report.

The program outlined here builds on that of three previous reports[1,2,3] prepared by the Cosmic Ray Program Working Group in 1982, 1985, and 1987. Responding to the evolving programmatic opportunities and constraints of the overall NASA program at the time, those reports developed a coherent program of research in cosmic rays that would address the general recommendations for the discipline outlined in the 1982 Astronomy Survey Committee (G. B. Field, chairman).

In the last year, most of the missions described in those earlier Cosmic Ray Program Working Group reports have become part of the NASA program for the next decade, including the recent selection of the Astromag Facility and the Heavy Nuclei Collector for Space Station Freedom, the Advanced Composition Explorer, the Positron/Electron Magnetic Spectrometer for the Earth Observing System, and SAMPEX, a small Explorer. Thus, by the beginning of the next century many of the scientific objectives discussed in those reports should have been accomplished and there will be opportunities for new scientific thrusts.

There are now several long range studies underway to identify new directions for the NASA program, including another decadal Astronomy and Astrophysics Survey (J. N. Bahcall, chairman) by the National Academy of Sciences/National Research Council and a Space Physics Planning Study (G. L. Siscoe, chairman) by the NASA Space Physics Advisory Subcommittee. In addition, NASA has been asked to develop a Human Exploration Initiative that would require continued monitoring of the solar and geospace environment and could include the establishment of a lunar base that would offer the opportunity for observations from the lunar surface.

Because the planning horizon for these studies is well beyond that of the previous reports of the Cosmic Ray Program Working Group, the group was reconvened in order to consider the new opportunities and outline the objectives of a longer range program. This interim report briefly reviews the program currently approved for the next decade and formulates new science thrusts and identifies candidate missions that would be key attributes of a vigorous cosmic ray program in the first decades of the next century.

Table 1 summarizes the major scientific themes that are addressed by the program described in this report.

2. MISSION REQUIREMENTS FOR THE CURRENT PROGRAM

The NASA cosmic ray program for the 1990's will be centered around the development and launch of a number of recently selected missions. These missions and other key elements of the program are described briefly below and summarized in Table 2.

Table 1 - Science Themes

The Origin and Evolution of Matter - The diverse populations of high energy particles arriving near Earth provide samples of matter from other regions of the solar system and the galaxy. Comprehensive studies of the composition of these particles will make it possible to:

- Determine and compare the composition of the solar corona, the local interstellar medium, and galactic cosmic ray sources.
- Identify nucleosynthesis and galactic evolutionary effects that distinguish solar system and galactic matter.
- Search for evidence of special sources of cosmic rays, such as supernovae and Wolf-Rayet stars.
- Determine the time scales for the nucleosynthesis, acceleration, and confinement of cosmic ray nuclei in the galaxy.
- Identify the origins of antiprotons and positrons in cosmic rays, and search for anti-nuclei and other exotic particles of galactic or extragalactic origin.

Nature of the Heliosphere and the Interstellar Medium - The particles and fields of the nearby interstellar medium are presently hidden from our view by the solar wind that encapsulates us within the bubble called the heliosphere. Exploratory *in situ* measurements within and beyond the boundaries of the heliosphere will:

- Investigate the large-scale structure and dynamics of the heliosphere as it responds to solar variations on a variety of time scales.
- Investigate "anomalous" and galactic cosmic ray acceleration at the solar wind termination shock, including possible *in situ* observations.
- Measure directly particles and fields in nearby interstellar space, and investigate their role in the energy balance of the galaxy, and in shaping the heliosphere.
- Study particle propagation in interplanetary and interstellar space.

Cosmic Acceleration Processes - Particle acceleration is ubiquitous in nature and is one of the fundamental problems in space physics. Comprehensive studies of solar, interplanetary, and galactic particles spanning many decades in energy will test shock acceleration models on a wide range of scales, and allow us to:

- Study particle acceleration and interaction processes in solar flare events with orders of magnitude increased sensitivity.
- Search for evidence of continuous cosmic ray acceleration by supernova shock waves.
- Investigate the acceleration mechanisms and sites responsible for the highest energy particles in our galaxy.

Table 2 - The Cosmic Ray Program for the 1990's

The following missions, recently selected for development and launch during the coming decade, are the focus of the NASA cosmic ray program for the 1990's.

- **ACE** - An Advanced Composition Explorer to measure the elemental and isotopic composition of H to Ni nuclei over six decades in energy/nucleon, from solar wind to galactic cosmic ray energies.

- **Astromag** - A superconducting magnetic spectrometer facility for the Space Station, including powerful instruments that will extend particle and anti-particle spectroscopy into the GeV and TeV energy ranges.

- **HNC** - A Heavy Nucleus Collector for the Space Station that will measure the abundances of the heaviest elements in the periodic table.

- **POEMS** - A POsitron Electron Magnetic Spectrometer for the Earth Observing System that will measure electrons and positrons from the Galaxy and the Sun, and also solar γ-rays and neutrons.

- **SAMPEX** - A Solar, Anomalous, and Magnetospheric Particle Explorer to be launched as part of the Small Explorer Program to study low energy particles from a polar orbit.

In addition, the continuing cosmic ray program also includes the following key elements:

- **New Cosmic Ray Instruments** to be carried on spacecraft soon to be launched for the Ulysses, CRRES, WIND, and NOAA-I missions.

- **Global Heliosphere Initiative** - Extended exploration of the heliosphere and monitoring of the Sun with instruments on the existing interplanetary network of Voyager, Pioneer, Galileo, ICE, and IMP-8 spacecraft, soon to be joined by Ulysses and others.

- A vigorous **Balloon-Flight Program** will make it possible to develop and test new instrumentation, and to initiate new investigations of cosmic ray elements, isotopes, antiprotons, and positrons.

- An **Accelerator-Based Program** for testing and calibrating new detectors and for measuring nuclear cross sections critical to astrophysics and the Human Exploration Initiative

2.1 Small Instruments Outside the Magnetosphere or in Earth Orbit

Small Instruments on other Missions - Most cosmic ray experiments that have flown in space were carried on near-Earth or interplanetary spacecraft that included several small particle and fields experiments as well as other instrumentation. New instruments of this kind presently scheduled for launch in the early 1990's include (1) a cosmic ray element and isotope spectrometer to be launched on Ulysses in 1990 and carried out of the ecliptic and over the solar poles, where it will conduct a solar latitude survey of a variety of energetic particle components; (2) a similar spectrometer to be carried into Earth-orbit on CRRES in 1990; (3) a solar flare and galactic cosmic ray isotope spectrometer to be launched on WIND in 1992 and carried to the L_1 Lagrangian point as part of the ISTP program; and (4) a solar flare isotope spectrometer to be carried on NOAA-I. These instruments, the first two of which were originally scheduled for launch in the 1980's, will play important roles in the broader objectives of these missions and take the long-awaited next steps in energetic particle spectroscopy beyond ISEE-3.

ACE - The instruments on the Advanced Composition Explorer (ACE), one of two recently selected Explorer-class missions, have greatly increased collecting power and coverage, allowing coordinated and comprehensive measurements of the elemental, isotopic, and charge-state distributions of energetic particles of solar, interplanetary, interstellar and galactic origins. Definitive measurements will be made of the abundance of essentially all long-lived isotopes from H to Zn ($1 \leq Z \leq 30$), spanning the energy range from that of the solar wind ($\lesssim 1$ keV/nucleon) to that of galactic cosmic rays (several hundred MeV/nucleon). The prime objective of ACE will be to determine and compare the elemental and isotopic composition of several distinct samples of matter, including the solar corona, the interplanetary medium, the local interstellar medium, and galactic matter. To accomplish this, ACE includes six high-resolution spectrometers, each designed to provide the optimum, charge, mass, and charge-state resolution in its particular energy range, and each having a geometry factor 10 to 100 times greater than previous or planned experiments. ACE is presently expected to be launched in $\sim$1997 to an orbit about the L_1 Lagrangian point.

SAMPEX - The Solar, Anomalous, and Magnetospheric Explorer (SAMPEX) is one of four recently selected missions for the new Small Explorer (SMEX) program. Scheduled for launch on a Scout rocket in 1992, SAMPEX will measure energetic electron and ion composition from $\sim$0.4 to $\sim$200 MeV/nucleon in a near-polar orbit. Key objectives of SAMPEX include determination of the charge state of the "anomalous" cosmic rays (predicted to be a singly-ionized sample of the interstellar medium), and measurement of relativistic electrons precipitating from the magnetosphere which undergo interactions in the middle atmosphere that affect ozone depletion.

2.2 Large Detectors in Earth Orbit

Astromag is a superconducting magnetic spectrometer facility for particle astrophysics that has been selected as a Space Station Freedom attached payload. Earlier, the Cosmic Ray Program Working Group recommended the development and flight of a large, high-intensity magnet for the mass spectroscopy of high energy cosmic rays. To this end, the Astromag project was extensively studied and then named as a Space Station Facility. Three first-generation experiments have now been selected for the first use of Astromag: Wizard, LISA and SCIN/MAGIC.

Wizard utilizes precision tracking chambers, time-of-flight scintillators, transition radiation detectors, and state-of-the-art calorimetry to search for primordial antimatter and to determine the spectra of antiprotons, positrons, and light nuclei ($1 \leq Z \leq 8$) to high energies. Measurements with unprecedented precision will be made up to energies of the order of a TeV. These measurements will bear on a wide range of fundamental issues, including (1) the implications of cosmic ray antiproton and positron fluxes and possible antinuclei for Grand Unified Theories and super-symmetry theories in cosmology, (2) other possible origins for the enhanced abundances of antiprotons and positrons in cosmic rays; and (3) the nature of the acceleration and propagation mechanisms of galactic cosmic rays.

LISA, a Large Isotope Spectrometer for Astromag, will make the first direct measurements of cosmic ray isotopes at energies above 1 GeV/nucleon. Particle mass will be determined with velocity measurements provided by a series of Cerenkov counters and rigidity measurements provided by scintillating optical fiber trajectory detectors. Isotope measurements of nuclei from Be to Ni will include studies of iron-group isotopes which can determine the time delay between nucleosynthesis and cosmic ray acceleration, and studies of radioactive nuclei such as ^{10}Be, ^{14}C, ^{26}Al and ^{37}Cl over a range of relativistic time-dilation factors to probe the density and distribution of interstellar material. In addition, LISA will measure cosmic ray element abundances with high precision to nearly 1 TeV/nucleon and perform a sensitive search for heavy cosmic ray antimatter.

SCIN/MAGIC will study the Spectra, Composition, and Interactions of Nuclei (SCIN) at very high energies using Magnet Interaction Chambers (MAGIC) that include passive track-recording devices such as x-ray film, plastic track detectors, and nuclear emulsions. The abundances of protons, helium, and heavier nuclei will be measured up to energies approaching 10^{15} eV, and electron spectra will be measured to almost 10^{13} eV. This instrument will also study interactions of nuclei in a unique regime where the collision energy-densities may be high enough to produce a phase change in the nuclear matter to a "quark-gluon" plasma.

Following the completion of the experiments selected for the initial use of Astromag, there are a number of second generation experiments requiring continued use of this facility. These include higher energy isotope experiments, more sensitive antimatter searches and use of the magnetic field for a new approach to high-energy gamma-ray spectrometry. The facility and its large-volume high-intensity magnetic field may also be used for other investigations such as plasma physics experiments.

HNC, the Heavy Nucleus Collector selected for deployment on Space Station Freedom, is a large-area (16 m^2) array of glass track detectors which will determine the elemental composition of heavy ($Z \gtrsim 50$) cosmic ray particles with high precision. With an exposure of several years, the HNC will measure the ratio of uranium to thorium with sufficient accuracy to answer the crucial question of whether cosmic rays are freshly synthesized material recently ejected from supernovae, or simply old interstellar material accelerated indirectly by passing supernova shock waves. HNC will also search for transuranium nuclei such as Pu, Np, and Cm that would be expected in fresh nucleosynthesis products.

POEMS, the POsitron Electron Magnet Spectrometer, will make the first space-based investigation of the positron spectrum in the energy range below 1 GeV, thereby complementing investigations on Astromag at higher energies. These investigations should resolve the question of whether cosmic ray positrons are accelerated in the sources as "primaries" or produced as "secondaries" by interactions of heavier cosmic rays during their transport through the galaxy. POEMS will also measure solar gamma-rays, neutrons, and electrons, and it will investigate cosmic ray modulation by tracking the effects of charge-sign-dependent processes such as drifts in the interplanetary magnetic field. POEMS is currently scheduled to fly on the first Eos polar-orbiting platform.

2.3 The Global Heliosphere Initiative

During the 1990s an impressive array of spacecraft instrumented for cosmic ray investigations and related studies of heliospheric and solar phenomena will be in place. Pioneers 10 & 11 and Voyagers 1 & 2 will be exploring the regions beyond 50 AU from the Sun, with Pioneer 10 heading down the heliospheric tail and the others heading towards the solar apex, returning data from the mid-latitude regions above and below the ecliptic plane. In the inner heliosphere, the IMP-8 and ICE spacecraft will be monitoring the solar wind, cosmic ray, and solar particle intensity near 1 AU, close to the solar input that drives the dynamics of the heliosphere. These veteran spacecraft will soon be joined by others, including Ulysses, as it embarks on a solar latitude survey of the spectra and composition of a variety of particle species.

This network of spacecraft represents a uniquely powerful configuration for studying the large scale structure and dynamical processes in the heliosphere and for locating and characterizing the heliospheric boundary. The opportunities which this network provides for simultaneous measurements at a variety of heliospheric radii and latitudes will not be duplicated in the foreseeable future. The instruments at 1 AU provide critical baseline measurements for the spacecraft at large radii and high latitudes, making it possible to distinguish spatial and temporal variations in the observations.

During the 1980s, measurements from this array of spacecraft revolutionized our understanding of the heliosphere and its interactions with energetic particles. Equally significant returns can be expected from continued tracking and analysis of data from these spacecraft in the future. These missions should continue to have strong support in NASA's program for the 1990s and beyond.

2.4 Missions of Opportunity

Currently under discussion are joint US-Soviet flights of two cosmic ray experiments on the Soviet space station MIR that could take place within the next few years.

CRN, the Cosmic Ray Nuclei detector, was flown several years ago on Space Shuttle Challenger, where it successfully demonstrated its capabilities for determining the charge and energy spectra of very high energy cosmic ray nuclei, albeit with limited statistics due to an exposure time of only a few days. CRN should be considered for a second, much longer deployment in space. A one year deployment would allow CRN's transition radiation detectors to realize their potential for determining the high energy cosmic ray composition of nuclei from boron to iron up to energies of $\sim$10 TeV/nucleon (corresponding to an energy of nearly 10^{15} eV for Fe nuclei).

Also under discussion for flight on MIR is a small version (1 to 3 m^2) of the glass detectors to be used in the Heavy Nucleus Detector (HNC) selected for flight on Freedom. For a two year exposure in MIR's 51.6 degree inclination orbit the yield of $Z>60$ ultraheavy nuclei for a 2 m^2 detector would be $\sim$15% of that expected for a 5 year exposure of the full HNC detector in the 28.5 degree orbit planned for Freedom.

3. MISSION REQUIREMENTS FOR THE LONG-RANGE PROGRAM

The long-range program described below and summarized in Table 3 includes new science thrusts and candidate missions for the first part of the 21st century.

3.1 Cosmic Ray Studies with an Interstellar Probe

The particles and fields of the local interstellar medium are excluded from the heliosphere by the solar wind and its embedded magnetic field. In our present view the solar wind flows radially outward to a termination shock, surrounded at somewhat greater distances by a heliopause, the boundary between the solar wind plasma and the interstellar gas. Theoretical models, supported by observations from Pioneer, Voyager, and other spacecraft, show that the interplanetary magnetic field, by means of processes known collectively as "solar modulation", shields the inner heliosphere from any direct knowledge of the composition, spectrum, and energy density of cosmic rays in interstellar space below several hundred MeV/nucleon, as well as significantly modifying the spectra of higher

Table 3 - New Thrusts for the 21st Century

- An **Interstellar Probe** is required to extend direct measurements of cosmic rays and related phenomena beyond the heliosphere and to assess their role in the energy balance and dynamics of the local interstellar medium and the galaxy.

- A **Lunar-based Calorimeter** would determine the composition and investigate the origin of cosmic rays up to $\sim 10^{16}$ eV, where a "knee" in the energy spectrum suggests the onset of effects due to acceleration limitations, galactic escape, or new cosmic ray sources.

- **Ultra-Heavy Nuclei** - Two new missions would study the synthesis of cosmic ray nuclei in the upper 2/3 of the periodic table, and measure nucleosynthesis and acceleration time scales with radioactive "clocks" that include U, Th and heavier nuclei.

    - A large area electronic spectrometer in Earth orbit or on a lunar base that would measure ultra-heavy elements from $Z \simeq 30$ to $Z \simeq 100$.

    - An Explorer mission to measure the isotopes of ultra-heavy nuclei in solar flares and in galactic cosmic rays.

- **Solar Flare Studies at 0.4 AU** - A solar particle spectrometer on the Mercury Orbiter mission would provide greatly increased sensitivity for studying solar flare acceleration and injection from a vantage point close to the Sun.

Other Initiatives

- As a complement to the energetic particle measurements from the Advanced Composition Explorer (ACE) and other missions, a Small Explorer mission to measure the spectra of γ-rays and neutrons emitted in solar flares would provide valuable additional information.

- To insure continued progress in defining the large-scale structure and dynamics of the heliosphere it is important that appropriate particle and fields instrumentation be included on all future interplanetary spacecraft.

energy particles up to about 10 GeV/nucleon. To observe interstellar cosmic rays one must get outside the heliopause. We propose a dedicated Interstellar Probe mission that would cross the termination shock and heliopause and make a significant penetration into interstellar space, thereby providing invaluable *in situ* measurements of the particles and fields in nearby regions of the Galaxy.

Present estimates place the solar wind termination shock at 40 to 100 AU, with the heliopause approximately a factor of two more distant. One or more of the Pioneer or Voyager spacecraft may well cross the termination shock within their lifetimes, but it is much less likely that the heliopause is within reach of Voyager's potential range of ~130 AU, to be reached in ~2015. Although these spacecraft may locate the termination shock and heliopause and return unique exploratory data, detailed studies will require modern instrumentation designed to comprehensively observe the interstellar medium. Recent studies by JPL show that an Interstellar Probe could be accelerated to a velocity of 10 to 20 AU/yr, thereby overtaking the Voyagers within a few years, reaching a distance of 200 AU within 10 to 20 years, and then possibly continuing out to 500-1000 AU in an extended mission.

An Interstellar Probe to the nearby interstellar medium could make a wide range of *in situ* measurements, including: the structure of the distant heliosphere; the acceleration of the "anomalous" cosmic rays and other species at the solar wind termination shock; the unmodulated interstellar spectra and composition of low-energy cosmic ray nuclei and electrons; the composition of the local interstellar gas; the interstellar magnetic field and other parameters required to understand cosmic ray transport; and the cosmic ray contribution to the heating, pressure, and energy balance of the local interstellar medium. In addition, measurements could be made of the ~1 MeV positrons from ^{56}Co decay in supernovae that are likely responsible for the galactic 0.5 MeV γ-ray flux, and a search could be made for cosmic ray anisotropies due to recent supernovae or nearby sources. In view of the fundamental importance of such measurements to a wide range of studies that include cosmology, stellar and galactic evolution, nucleosynthesis, and space plasma physics, it is important that NASA give serious consideration to the development of this truly exploratory mission.

3.2 Very High Energy Cosmic Rays

The spectrum and composition of cosmic rays at energies above 10^{15} eV/nucleus is an area of intense interest. There is a distinct change in slope, or "knee" in the all-particle energy spectrum near 10^{16} eV, suggesting that at higher energies nuclei may have a fundamentally different origin and composition than at lower energies. Because of the low fluxes, however, direct measurements of nuclei with 10^{15} to 10^{17} eV are very difficult. Current balloon- and space-based experiments are too small to provide good statistics in this region; presently the only information comes from indirect Earth-based measurements of extensive air showers.

There are suggestions of very interesting astrophysics and particle physics at these high energies. It is presently thought that acceleration of particles to $\gtrsim 10^{16}$ eV would require larger scale shocks than are presently thought to be possible in the galactic disk, and cosmic rays may also escape more efficiently from the galaxy at these energies. In addition, balloon observations have given indications of a nuclear matter phase change in the interactions of very high energy cosmic ray nuclei, and ground-based measurements have suggested that the ratio of hadronic to electromagnetic interactions of photons may be rapidly increasing at these energies.

A Lunar-Based Calorimeter - In order to measure the primary spectrum and composition at 10^{16} eV with reasonable statistical precision, a collecting power of $\sim$100 m^2sr and an exposure time of $\sim$5 years will be required. The corresponding weight of such a calorimeter, if designed for space flight, would be $\sim$100 tons. Since this is probably too heavy to be flown in orbit, a lunar-based detector, fabricated primarily from lunar material, probably offers the only practical means for building the experiment. The bulk of the calorimeter material would be compressed lunar regolith; only relatively light plastic scintillators, electronics, and support structure would be carried up from Earth. A calorimeter with a collecting power of $\sim$100 m^2sr could use several hundred tons of lunar soil as the calorimeter material, but only a few per cent of this mass would need to be brought to the Moon. Elements from protons through iron would be measured with good precision at energies above the "knee" in the all-particle spectrum.

A Space-Based Calorimeter - A large space-based calorimeter (25 m^2sr with a 3-4 year exposure) would provide a major improvement over the SCIN/MAGIC experiment on Astromag for charges $Z = 1$ to 5 and over CRN for heavier nuclei, and, in addition, would be an important intermediate step leading to a still larger lunar calorimeter. A 25 m^2sr calorimeter, weighing $\sim$25 tons, could be flown as a Large Attached Payload on a second generation Space Station, or it would be a candidate for a joint US-Soviet mission or other international collaboration. Such a possibility warrants detailed study.

3.3 Ultraheavy Nuclei Studies

A Large-Area Spectrometer for Ultraheavy Elements - Measurements of the elemental composition of elements beyond the iron peak are of special interest because of the information they carry about neutron-capture nucleosynthesis processes that have forged the upper 2/3 of the periodic table, and because they include a number of radioactive species that can be used as "clocks", particularly among the "actinide" group of elements that include Th, U, and possibly transuranic nuclei. The Heavy Nucleus Collector (HNC) selected for Space Station Freedom will use passive track detectors with an area of 16 m^2 to measure UH nuclei with $Z \gtrsim 50$. A total of $\sim$40 actinides (with a sizeable uncertainty) is expected by HNC in a four year exposure.

It appears that the next step beyond HNC would be a detector with at least an order of magnitude increase in collecting power. Such a detector could provide accurate measurements of the clocks in the actinide region, and provide a sensitive search for transuranic nuclei that would signify recent nucleosynthesis contributions to cosmic rays. This next instrument should also be capable of providing fully resolved measurements of elements with $30 \leq Z \leq 50$. A large part of the required increase in collecting power might be achieved by placing this instrument in a high-inclination orbit, or outside the magnetosphere, perhaps on a lunar base. Because passive detectors require recovery, it presently appears that a large array of electronic detector modules is the best approach for achieving the required collecting power. One such modular concept, called "C-Shell", is based on Cerenkov and time-of-flight measurements. As there are a number of possible approaches, including a lunar-based instrument or in-orbit assembly of large arrays, it is important that NASA study options for satisfying this very significant objective.

An Explorer for Solar/Galactic Ultraheavy Isotopes - The currently approved investigations of energetic heavy nuclei will explore in depth the nucleosynthesis of solar and galactic material for elements from hydrogen to nickel ($Z \leq 28$). The extension of composition studies to provide isotopic abundances of ultraheavy elements ($Z > 28$) will make it possible to investigate the neutron-capture nucleosynthesis processes responsible for production of more than 3/4 of the stable nuclides. Preliminary information about isotopes up to $Z \simeq 40$ will be provided by instruments on ACE, but the detailed study of these rare species, and those above $Z = 40$, will require new large area instrumentation exposed outside the Earth's magnetosphere for a period of several years. These objectives can be met by an Explorer-class spacecraft dedicated to the measurement of the isotopic composition of ultraheavy elements in both solar energetic particles and galactic cosmic rays. Presently, the mass resolution needed for these measurements has been realized only for low energy particles ($\lesssim$1 GeV/nucleon) which are prevented from reaching low Earth orbit, except at high latitudes, by the geomagnetic field. To achieve the necessary exposure outside the magnetosphere, these measurements should be carried out in an orbit at $\gtrsim$20 Earth radii. Alternative approaches include use of a polar orbiting platform in low Earth orbit (for which low energy particles can be collected over ~30% of the orbit) or lunar based instruments.

The large-area sensor systems needed for ultraheavy isotope measurements up to $Z=40$ and possibly higher can be realized as extensions of detectors now under development or planned for balloon experiments and for ACE. For galactic cosmic ray studies, options include measurement of dE/dx vs. total energy using ionization detectors (either solid state or gas) and measurement of Cerenkov emission vs. range (or energy). For solar flare isotopes, large time-of-flight vs. total energy sensor systems should provide the needed resolution and statistics. Continuing development of these types of detectors using high altitude balloon exposures and accelerator beam tests is essential for realizing the goals of ultraheavy isotope investigations.

3.4 Solar Energetic Particle Studies

Impulsive Solar Flare Studies from a Mercury Orbiter - The Mercury Orbiter (MeO) mission offers a unique opportunity for obtaining solar energetic particle (SEP) observations that can answer long-standing, fundamental questions about the flare process and the solar corona itself.

An MeO solar energetic particle instrument could make fundamental observations of the two major types of solar flares: (1) large solar particle events, and (2) small, impulsive events which show enrichments in ^{3}He, heavy ions, electrons, and (sometimes) gamma rays. The large solar particle events are associated with Type II and IV radio bursts caused by coronal shock waves. However, since the energetic particles are scattered many times on their path to 1 AU, observations at Earth orbit cannot separate the effects of particle injections extended in time versus particle scattering and storage near the Sun. Overall, the most convincing physical picture is that in large solar particle events the long injection time scales reflect acceleration at the Sun due to large shocks moving through the corona, accelerating particles out to tens of solar radii. While this and other possible scenarios cannot be conclusively proved or disproved with current observations, a solar particle instrument on MeO, located at 80 solar radii, would immediately resolve this fundamental question since the shocks could come near to, or even pass by, the spacecraft in the main acceleration phase.

Although the large solar particle events produce the greatest fluxes of accelerated nuclei, they occur much less frequently than small impulsive flares. Exploratory studies of impulsive flares have been carried out at 1 AU, but detailed studies of this most common type of solar particle event have been limited by their small intensity which is adversely affected by propagation to 1 AU. However, at 0.4 AU the flux risetime is extremely short, allowing the time of particle injection at the Sun to be determined to within a few minutes, providing crucial information for comparing with MeO gamma-ray and neutron observations. Observations at 1 AU, on the other hand, cannot establish particle injection times more accurately than $\sim$15-20 minutes due to wandering of the interplanetary magnetic field. In addition, at 0.4 AU peak fluxes are several hundred times greater than those at 1 AU, due to the combined effects of magnetic field divergence and velocity dispersion. Thus, MeO observations can make unambiguous determinations of abundances and charge states from flares which cannot even be observed at Earth orbit because of dilution with other classes of particles.

The low frequency of large events makes it likely that no such event would occur during the short period when Solar Probe is closer than 0.4 AU to the Sun. On the other hand, MeO will spend years close to the Sun, ensuring that many solar particle events of both classes will be observed.

A Small Explorer To Conduct Solar Flare Gamma-Ray Observations in Conjunction with the Advanced Composition Explorer - One of the most important results of recent solar flare studies is the finding that ions and relativistic electrons are routinely accelerated in impulsive solar flares, and that such acceleration is an intrinsic property of the flare energy release process. This was first demonstrated by Solar Maximum Mission (SMM) observations, which revealed the very impulsive nature of the solar flare gamma-ray emission. Recent energetic particle observations of solar flares support and elaborate on this result: impulsive flares reveal enhanced ^{3}He, heavy ion and relativistic electron abundances, as well as highly stripped Fe ions whose charge state is much more characteristic of hot flare plasma than of the million-degree corona. Prior to the SMM it was thought that ion acceleration in solar flares is a just by-product of the main energy-release event, manifest only in large interplanetary proton events.

The simultaneous observation of accelerated particles, gamma rays, and neutrons from impulsive solar flares would have significant scientific merit. Gamma-ray line emission and accelerated particles provide the only unambiguous signatures of ion acceleration in solar flares. Among the many correlated studies, perhaps the most important will be the simultaneous determination of the elemental and isotopic abundances of the particles suffering nuclear interactions at the Sun and those which escape from the Sun. The former can be determined from high-resolution gamma-ray spectroscopy; the latter from accurate charged particle observations. Abundance determination is perhaps the most powerful technique in cosmic evolution studies, and is central to all of particle astrophysics. But only for solar flares can abundances be simultaneously determined inside a source and in the accelerated particles which escape from it. In addition, the correlated gamma-ray and particle observations can also provide unique information on particle acceleration, escape and transport, which are central issues to the study of cosmic ray origin.

The required gamma-ray observations could be carried out with an array of Ge detectors flown on a Small Explorer launched while ACE and possibly Wind are operating in the mid to late 1990's. With a mechanical cooler, this instrument could remain operational for up to a decade, thereby carrying out solar observations over the entire cycle 23.

3.5 The Explorer Program

This highly successful program has traditionally been the means by which relatively inexpensive missions dedicated to well-focussed objectives could be flown. Recently a line of Small Explorers was added in an effort to provide more rapid access to space for new, low-cost experiments. Within the Cosmic and Heliospheric Branch the Advanced Composition Explorer (ACE) and a Small Explorer (the Solar, Anomalous, and Magnetospheric Particle Explorer - SAMPEX) were recently selected for development. This report also identifies an Ultraheavy Isotope Explorer and a Small Explorer for solar gamma-rays as two additional concepts that can provide high-priority science within the Explorer framework. As another example, a dedicated Explorer to conduct coordinated measurements of solar flare nuclei, electrons, neutrons, γ-rays, and x-rays during solar cycle 24, preferably inside of $\sim$0.5 AU, would be an important next step beyond ACE, MeO, and the solar flare gamma-ray Small Explorer discussed above.

As indicated by these examples, we are confident that there will continue to be a need for Explorer-class missions within the cosmic physics discipline. These requirements could be met by the suggested establishment of an independent line of Space Physics Explorers.

4. OTHER PROGRAM ELEMENTS

4.1 Small Instruments on Spacecraft Leaving 1 AU

The Heliosphere is a dynamic structure that undergoes major changes over the 22-year solar cycle, significantly affecting the flow of cosmic rays into the inner solar system. The Global Heliosphere Initiative makes use of a number of spacecraft in deep space to study the three dimensional properties of the heliosphere at ever-increasing distance from the Sun. After 1996, however, there will be no observations in the middle heliosphere (5 to 30 AU) unless appropriate instruments are included on future spacecraft leaving 1 AU. Unfortunately, this cost-effective approach is threatened by the exclusion of even modest instruments on future missions, and by the exclusion of any cruise-phase measurements. This recent trend undermines a proven and successful strategy for achieving important objectives at minimal incremental costs to the mission. Appropriate cruise-phase science should therefore be included in the operating plans for future spacecraft leaving 1 AU.

4.2 Balloon-Borne Instruments

The balloon program remains an indispensable part of particle astrophysics. Its main functions are (i) development of new experimental techniques, (ii) test and verification of space instrumentation, and (iii) pursuit of specific science goals that are commensurate with the capabilities of the balloon vehicle. Furthermore, balloon borne investigations play an irreplaceable role in the training and education of students and young scientists: they provide hands-on experience and the opportunity for quick response to new scientific questions. Their low cost, as compared to space vehicles, permits the taking of some risks that are inherent in truly innovative approaches. The following are examples of activities for which there is no practical alternative to the use of balloons:

(1) Experimental techniques: development of advanced particle detectors, such as aerogel and ring-imaging Cerenkov counters, scintillating fiber detectors, transition radiation detectors, and high pressure gas ionization chambers. In some cases, such techniques are adapted from applications in the laboratory and at accelerators, in others they are specifically developed for particle astrophysics applications.

(2) Verification of space instrumentation: test of the performance of magnet spectrometer systems and the resolution of trajectory measuring devices and time-of-flight systems within a near-space environment.

(3) Science goals: As the load carrying capability of balloons is quite substantial (~2-3 tons), and flight durations of days or perhaps even weeks are possible, a number of significant investigations can be pursued, including measurements of isotope abundances to ~1 GeV/nucleon, observations of electrons, positrons and antiprotons over a fairly wide energy region, and measurements of the energy spectra of the more abundant particle species to ~100 GeV/nucleon.

An adequate level of support for the balloon program and enhanced funding for state-of-the-art detector developments are essential for the future of the discipline.

4.3 Cosmic Rays and the Human Exploration Initiative

Manned exploration missions will require a better understanding of the effects of human exposure to galactic cosmic ray and solar energetic particle fluxes. This will involve questions of long-term exposure to galactic cosmic rays (for example, on a long-duration Mars mission or an extended tour of duty at a lunar base) and transient exposure to the particle fluxes from intense solar flares. Determination of realistic shielding requirements for extended missions demands accurate measurements of the temporal and spatial dependence of the observed cosmic ray fluxes, spectra, and composition, and depends on an accurate assessment of the attenuation of cosmic ray fluxes by shielding. Real-time and near-real-time measurements throughout the heliosphere will be provided by CRRES, Wind, ACE, and the network of spacecraft comprising the Global Heliosphere Initiative. Improved and updated measurements, together with an expansion of the existing program of interstellar and interplanetary propagation studies, will make possible significantly improved predictions of baseline flux levels, long term variations over the solar cycle, and short term variations due to heliospheric fluctuations.

An accurate assessment of shielding efficiency requires improved knowledge of nuclear interaction cross sections, particularly those for neutron production and those below a few hundred MeV/nucleon where present data are sparse. To accomplish these goals will require a vigorous program to measure the relevant heavy ion cross sections at the Bevalac.

4.4 Theory and Laboratory Investigations

Theory - There is a continuing need for theoretical investigations to support the scientific objectives of NASA's particle astrophysics program. Selected topical meetings that bring together theorists with different but related interests, as well as experimentalists, will be an effective addition to the ongoing Theory Program of the Cosmic and Heliospheric Branch. A timely example would be an international topical conference on acceleration and transport of energetic particles at all scales and energies including interplanetary, heliospheric, galactic and extragalactic.

Accelerator Facilities - The Bevalac heavy ion accelerator at Lawrence Berkeley Laboratories has become an essential support facility for the field. The scientific significance of the observed abundances of cosmic ray nuclei depends critically on detailed knowledge of the nuclear cross sections, which can only be measured systematically at the Bevalac. Although a modest beginning in the measurement of these cross sections has been made, much more work is needed if full advantage is to be taken of present and future observations of cosmic ray abundances. The development and calibration of particle detectors also requires exposure to Bevalac heavy ion beams. NASA programs have traditionally been allocated some 200-300 hours of running time per year. This has become inadequate to meet the need, and additional running time is urgently needed to meet present requests. The anticipated shutdown of the Bevalac in 1994-5 will represent a serious loss to the field and it is not clear how it will be replaced. The only comparable facility is the GSI(Darmstadt)-SIS facility, expected to come on line in 1990. Whether NASA programs can obtain running time on this nuclear physics facility is unknown but probably unlikely. It is therefore important that NASA work with the relevant agencies and governments to ensure that sufficient access to appropriate accelerator beams is available for instrument calibrations and cross section measurements in the future.

The Cosmic Ray Neutron Monitor Network Over the past four decades the world-wide network of neutron monitors, now consisting of 60 stations, has provided the only continuous measurements of the high rigidity (>1 GV) galactic cosmic ray flux, as well as making measurements of high energy particle fluxes in solar flare events. Neutron monitor measurements of the modulated cosmic ray spectrum now extend over nearly two complete 22-year solar magnetic cycles. Although neutron monitors respond mainly to secondaries resulting from the interaction of high energy protons in the upper atmosphere, recent measurements have been made of direct neutrons from solar flares, thus providing invaluable insights into the solar flare acceleration process. Observation of these very rare neutron events requires a combination of large geometrical factor, high proton cutoff rigidity, and good time resolution. It is critical to maintain the present neutron monitor network to support space-based studies of cosmic and heliospheric phenomena.

4.5 Infrastructure and Resources

The cosmic ray astrophysics program, like all programs of space exploration, is focused towards a small number of missions, such as ACE, Astromag, or a future Interstellar Probe. A significant fraction of the resources available at NASA must be dedicated to the support of such missions. However, each mission takes many years from inception to launch. These time scales present a serious problem for the participation of the scientific community, in particular at universities. Although a first rate program requires contributions from innovative young scientists and students, such individuals often find themselves in a critical "publish or perish" phase of their career and may turn towards other fields unless a scientific infrastructure exists that permits creative work on a time scale shorter than that of the longer term space missions. This work might include data analysis from previous space ventures, but it must also permit experimental activities that are at the cutting edge of technology.

It is therefore essential for the future of the field that opportunities and resources be available to the scientific community for the training of young scientists, for innovative detector development in the laboratory, for Guest Investigator programs on flight missions, for short-turnaround observations in sub-orbital missions such as balloons, and for quick access to space as provided by Small Explorers or payloads attached to the Space Station. And it is essential that an adequate level of basic funding be made available for such work.

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